

NACA TN 3025

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE 3025

AN INVESTIGATION UTILIZING AN ELECTRICAL ANALOGUE
OF CYCLIC DE-ICING OF HOLLOW STEEL PROPELLERS
WITH INTERNAL ELECTRIC HEATERS

By Carr B. Neel, Jr.

Ames Aeronautical Laboratory
Moffett Field, Calif.



Washington
October 1953

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE 3025

AN INVESTIGATION UTILIZING AN ELECTRICAL ANALOGUE OF CYCLIC DE-ICING OF HOLLOW STEEL PROPELLERS WITH INTERNAL ELECTRIC HEATERS

By Carr B. Neel, Jr.

SUMMARY

A study has been made of the heating requirements for the cyclic de-icing of hollow steel propellers fitted with two types of internal electric heaters. Solutions to the transient-heat-flow equations depicting the cyclic de-icing of propellers were obtained by use of an electrical analogy. The study showed the impracticability of using an internal tubular heater and illustrated the advantages of employing an internal shoe-type heater, which distributes the heat more evenly to the blade surface. The importance of minimizing the thermal inertia of the system was demonstrated, and the magnitude of reductions in the total energy requirement made possible through reductions in the heating period was indicated.

INTRODUCTION

External electrical blade-heating shoes have been used extensively for propeller ice protection. Exposure of these shoes to the abrasive action of foreign matter in the air and their vulnerability to other damage has caused considerable maintenance difficulty. As a means for alleviating the maintenance problem, electric heaters mounted inside the propeller blades have been considered. Although several types of internal heaters have been proposed, only one type has been used in service. Up to the present time, experimental data have been obtained for only this one configuration, which consists of a shoe-type heater installed in a hollow steel blade with a thin sheet-metal outer skin. Reference 1 describes icing-tunnel tests of this arrangement, while reference 2 presents a continuation of the study by means of an electrical analogy for simulation of the heat flow. Since only one arrangement was investigated, further tests were required to provide a coverage of other possible arrangements of internal heaters.

This report deals with simulated cyclic de-icing of propellers fitted with internal electric heaters, and constitutes the second phase

of a general investigation of propellers protected against icing by means of heater elements installed on either the external or the internal surface of the blade. The first phase treated external blade-heating shoes (ref. 3). In the present investigation, data were obtained for two types of internal heaters installed in a hollow steel propeller. Inasmuch as experience has shown that intermittent heating provides a more economical utilization of power than continuous heating, data were obtained only for the case of cyclic de-icing.

As in the tests of references 2 and 3, an electrical analogue was used to simulate the cyclic de-icing of a propeller blade. Data were obtained which showed the effects of variations in cyclic ratio (ratio of heating period to total-cycle time) and heater design on the heating requirements.

DESCRIPTION OF EQUIPMENT

The equipment used in this investigation was the same as was employed in the study reported in reference 3. For this reason, only a brief description of apparatus will be presented; more detailed information may be obtained from reference 3.

Electrical Analogue

The electrical analogue used to simulate the transient heat flows is shown in figure 1, and consists essentially of a network of electrical resistances and capacitances connected in such a manner as to simulate a thermal circuit. In the electrical circuit, electrical resistance and capacitance represent thermal resistance and capacitance; current flow represents heat flow; and voltage difference represents temperature difference.

Special Circuits

A number of special circuits were employed to simulate the boundary and input functions representative of a cyclically heated propeller in icing conditions. A constant-current source connected to a switching system provided the electrical arrangement representative of the cyclic application of heat. Additional constant-current circuits were arranged to simulate the application of heat at the blade surface resulting from aerodynamic heating and release of the heat of fusion of the supercooled drops impinging on the blade surface as they solidified to ice. Relay circuits were used which switched in resistors and condensers to typify the continuous growth of ice on the blade after

each removal process. Other circuits, termed "heat-of-fusion" circuits, were provided to simulate the melting of those regions of the ice formation which reached the melting point before release of the ice. This was accomplished by retaining these regions at a constant voltage representative of 32° F until simulated removal of the ice was attained.

Measuring Equipment

An oscillograph was used to record voltage changes representative of the temperature changes occurring during cyclic heating.

CONFIGURATIONS OF PROPELLER BLADES, HEATERS, AND ICE FORMATION

Propeller Blades and Heaters

The study was limited to the 48-inch radial station of the propeller. It was believed that this would provide representative data for the entire propeller, since the heating requirements have been shown to vary only slightly with radial station (ref. 3). The blade sections at the one station analyzed are shown in figure 2. The blades shown in this figure are typical of one form of blade construction currently in use.

Two types of internal heaters were investigated. These were a tubular-type heater and a shoe-type heater, as illustrated in figure 2. The tubular heater was chosen for study, inasmuch as it has been considered for use by the U. S. Air Force. The shoe-type heater was investigated to show the effect of a more efficient heater arrangement. In this case, the propeller blade was assumed to be identical to that containing the tubular heater, with the exception that the leading-edge fillet was eliminated, and the blade-metal thickness was taken as being uniform throughout the entire blade.

Ice Formation

The shape of the ice formation considered in the investigation is shown in figure 2. The chordwise extent of the formation was based on calculations of the farthest aft point of water-drop impingement by use of the data of reference 4, while the shape of the accretion was based on photographs of actual ice formations and on experience with the accretion of ice on propeller blades.

Physical Properties and Division of Blade, Heaters,
and Ice Formation for Analogue Study

The physical properties adopted for the blade metal, heater materials, and ice layer are presented in table I. In the study of the shoe-type internal heater, the properties of the insulating material were varied from the values shown in table I to determine the effect of such variations on the heating requirements. The program of these variations is presented in the following table. In this table, R and C represent the thermal resistance and capacitance of the insulation material, and each is assigned a value of unity for the case of a rubber insulation layer 0.03 inch thick.

Configu- ration	Primary insulation (between heater and blade)	Backing insulation	Effect studied
1	none	none ($R = \infty$)	No primary or backing insulation
2	0.03 in. rubber ($R \times 1, C \times 1$)	none ($R = \infty$)	Variations in properties of primary insula- tion
3	$R \times 1, C \times 1/2$	none ($R = \infty$)	
4	$R \times 1/2, C \times 1$	none ($R = \infty$)	
5	0.03 in. rubber	0.03 in. rubber ($R \times 1, C \times 1$)	Variations in properties of backing insula- tion
6	0.03 in. rubber	$R \times 1, C \times 1/2$	
7	0.03 in. rubber	$R \times 2, C \times 1$	
8	0.006 in. glass cloth with binder	0.006 in. glass cloth with binder	Proposed configu- ration with improved thermal characteristics

In the analogue study, the blade, heaters, and ice formation were divided into regions, throughout which conditions were assumed uniform. These divisions are illustrated in figure 2. As in the investigation of reference 3, the ice was divided into three layers, each of which was

switched into the circuit in sequence to represent the continuous growth of the ice.

OPERATING AND METEOROLOGICAL CONDITIONS SELECTED FOR ANALOGUE CALCULATIONS

Airplane Operating Conditions

The airplane operating conditions selected for all the calculations were chosen as being typical of those for transport airplanes currently in operation, and were as follows:

Forward true airspeed	300 mph
Propeller rotational speed	1100 rpm
Pressure altitude	20,000 ft

Blade-Heater Operating Conditions

A total-cycle-time duration of 80 seconds was maintained for all tests of cyclic heating. Four ratios of duration of heating period to total-cycle time were investigated, as follows:

Cycle ratio	Time on, sec	Time off, sec
1 to 4	20	60
1 to 8	10	70
1 to 11.4	7	73
1 to 16	5	75

All four ratios were used in the analysis of the shoe-type heater. In the study of the tubular heater, data were obtained at all ratios with the exception of the 1-to-11.4 ratio.

In the investigation of the blade with the shoe-type heater, the distribution of heating intensity was adjusted to provide essentially uniform heating at the blade outer surface. To accomplish this, the analogue values were regulated so that the inner-surface heating intensity for each segment was proportional to the ratio of outer-surface area to inner-surface area.

Meteorological Conditions

The basic meteorological conditions selected were:

Liquid-water content	0.1 gm/m ³
Water-drop diameter	15 microns
Free-air temperature	-12° F

The liquid-water content of 0.1 gram per cubic meter was selected as a reasonable low value since low values of water content, combined with low air temperature, represent the most severe conditions for a propeller cyclic de-icing system (ref. 3). The air temperature of -12° F was computed from the data of reference 5 and was based on the probability of encountering a lower value of air temperature once in 1000 icing encounters for the conditions of 0.1 gram per cubic meter and 15-microns diameter. Data also were obtained at air temperatures of 0° and -20° F for configuration 8 only. No studies of the effect of a variation in liquid-water content were made, inasmuch as this effect was covered in the investigation of reference 3.

TEST PROCEDURE

Arrangement of Analogue Circuits to Simulate Cyclic De-Icing of a Propeller

Appropriate values of electrical resistance and capacitance were placed on the analogue to simulate the thermal circuit of the propeller blade. The heat-transfer equation used in the evaluation of the effective thermal resistance from the ice surface to the surrounding air and the equilibrium temperature of the ice surface is given in reference 3. In the computation of electrical values, a ratio of analogue time to actual time of 1 to 50 was used. Thus, a 1-second increment of time on the analogue represented a 50-second interval of time on the propeller blade.

Prior to gathering the transient-temperature data, the values of equilibrium surface temperature were adjusted for each of the blade segments. In the region of the ice cap, the heat-of-fusion circuits were set for all segments but the one exhibiting the smallest temperature rise. With the blade heater operating cyclically, the heater input intensity was adjusted so that the surface temperature of this segment just reached 35° F at the instant of termination of the heating cycle. It was assumed that this would assure a complete release of all portions of the ice formation.

Recording of Data

Separate records were taken of the temperature variations of the blade surface and the heater element during simulated cyclic de-icing. In many instances, heater-temperature data were obtained only for the segment which experience had shown displayed the highest temperature rise, inasmuch as only the maximum heater temperature was of primary concern.

RESULTS AND DISCUSSION

Blade With Internal Tubular Heater

Surface temperatures and required heating intensities.— Typical curves of the cyclic temperature variation of the blade surface and the heater element for the blade with an internal tubular heater are shown for one blade segment in figure 3. Figure 4 presents typical curves of the surface-temperature variation for the entire blade section. In these figures, it will be noted that the temperature of the surface continues to rise well after the heating has been terminated. The persistence in temperature rise after conclusion of heating is caused by release of the heat stored in the blade during the heating period, and indicates a large degree of thermal lag. This thermal inertia, which is created primarily by the large mass of metal surrounding the heater tube, is detrimental in a cyclically heated system, inasmuch as high heating intensities are required to enable the desired blade-surface temperature to be reached in the specified time interval. The heating intensities required for de-icing are shown as a function of heating period in figure 5, which also presents for comparison a curve for the case in which the heating is applied uniformly to the blade outer surface. These data show the heat requirements for the internal tubular heater to be much greater than for uniform outer-surface heating. From this comparison, it may be reasoned that the high heating intensities for the tubular heater are required for two reasons: (1) the large thermal inertia, as mentioned, and (2) the uneven distribution of heat at the blade surface. Regarding the heat distribution, an inspection of figure 4 reveals that the surface-temperature rise is not uniform, and, as a result, a substantial amount of heat is wasted in the melting of ice prior to its removal. The uneven heat distribution is a consequence of the relatively large distance from the heater to the blade leading edge, which causes the temperature at this point to lag below that of regions closer to the heater.

These results lead to the conclusion that the tubular heater considered herein is an inefficient heater arrangement. Furthermore,

it is believed that this conclusion would apply generally to all tubular-type heaters. It appears that considerable energy may be saved in an internal-heater configuration by a reduction in the mass of metal in the vicinity of the heater, and by a more uniform application of heat.

Heater-element temperatures.— Because of the large thermal inertia of the blade, the high thermal resistance of the insulation surrounding the heater element, and the uneven surface distribution of heat, very high heater temperatures are required to raise the temperature of the most critical blade segment to the ice-melting point. An illustration of the high values of heater temperature is given in figure 3, in which the temperature is shown to reach 590° F. The maximum heater temperatures ranged from 650° F for a 20-second heating period to 950° F for a 5-second heating period. These temperatures appear excessively high from a safety standpoint.

Modified Blade With Internal Shoe-Type Heater

In view of the low efficiency of the tubular-type heater, no further tests were conducted for this configuration; instead, consideration was given to a more efficient internal-heater arrangement. This arrangement is the shoe-type heater shown in figure 2(b).

Surface-temperature data.— Typical curves of the cyclic temperature variation of the blade surface and heater element for the blade with an internal shoe-type heater are given for one blade segment in figure 6. Figure 7 presents typical curves of the surface-temperature variation for the five blade segments under the ice accretion. These figures show that the surface temperature rises and falls quite rapidly upon application and removal of heat, indicating a relatively small amount of thermal inertia in comparison with that for the blade with the tubular heater. The data of figure 7 show that all blade segments tend to reach 32° F simultaneously; thus, the quantity of heat wasted in overheating particular areas is minimized. It appears, then, that the optimum heating distribution is one approximating a uniform supply of heat at the blade outer surface. It is of interest to note that this agrees with a similar conclusion reached in reference 6 concerning the optimum distribution of heat for external blade shoes.

Heater-temperature data.— Maximum values of heater temperature reached during simulated cyclic de-icing of the shoe-type heater are summarized in table II for the eight configurations studied. These data were obtained from curves of heater-temperature variation similar to that presented in figure 6. It is evident from the data of table II that the maximum heater temperatures are considerably less than those

obtained for the tubular heater, and from the temperature standpoint, use of the shoe-type heater is much more feasible than use of the tubular type. However, even for some configurations of the shoe-type heater, as the required heating intensity is increased with decreased heating period, the maximum heater temperature increases to the point where many insulation materials, such as rubber, would fail. The possibility of controlling the maximum heater temperature through appropriate design will be considered in a later section.

Effect of variations in properties of insulation material on heating requirements.—The configurations which were used to investigate the effect on heating requirements of variations in the properties of the primary insulation are those listed previously as configurations 2 to 4. In these cases, there was no backing insulation, and it was assumed that no heat was transferred into the stagnant air of the propeller cavity; that is, the thermal resistance inward was taken as infinite. Results of tests of the required heating intensity for de-icing as a function of the duration of heating period for these configurations are presented in figure 8. Also given for comparison are curves for the case of no primary or backing insulation (configuration 1), and for the case of an external heater with no outer insulation and perfect insulation between the heater and blade. Configuration 1 represents the extreme condition of minimum thermal resistance and capacitance, which is approached as the thickness of primary insulation is reduced, and indicates approximately the minimum heating requirements for this blade with an internal heater. The curve for the external heater was taken from figure 12 of reference 3, and shows the heating intensity required to raise the temperature of the under surface of the ice accretion alone to 32° F and, hence, represents the minimum heating necessary for ice removal under these conditions. Thus, a comparison of the curves for configuration 1 and the external heater illustrates the effect of the blade metal on the heating requirements. The values of heating intensity presented in this figure are those required at the blade outer surface, assuming a uniform distribution of heat at the surface in the region of the ice formation.

The data of figure 8 show that the use of a 0.03-inch-thick layer of rubber as primary insulation can increase the heat requirement considerably over that for no insulation at the short heating periods, but that it has a smaller effect at the longer heating times. Figure 8 also indicates that proportional decreases in thermal capacitance and resistance have about equal effect, and that substantial savings in power can be obtained at the shorter heating times by reasonable changes in the thermal properties of the primary insulation material. The presence of the 0.08-inch-thick blade metal more than doubled the heating intensity required for the ice alone at a 5-second heat-on time, but had very little influence at a heating period of 20 seconds.

The effect on heating requirements of variations in the properties of the backing insulation, with a 0.03-inch-thick layer of rubber for primary insulation, is shown in figure 9, which presents data for configurations 5 to 7. The curve for configuration 2 is also shown for a basic comparison, since this represents the minimum required heating values which are approached as the thickness of the backing insulation is reduced. It is apparent from these results that the existence of a backing layer consisting of 0.03-inch rubber has a large influence on the heating requirement at short heating times, and that large changes in the thermal properties are required to obtain substantial reductions in the necessary power. However, at heating periods of about 20-seconds duration, the presence of the backing insulation does not have as great an effect on the heating requirement. The data of figure 9 show that reducing the thermal capacitance of the 0.03-inch rubber backing layer by a factor of 2 has about the same effect as increasing its thermal resistance by the same factor.

In view of the fact that the data for rubber primary and backing insulation layers showed that substantial gains in heat economy were to be obtained through appropriate changes in the thermal characteristics of these layers, especially at the shorter heating times, further studies were made to determine the heating requirements for a shoe-type heater with improved thermal characteristics. This configuration is listed as number 8 in the table presented previously, and consisted of 0.006-inch-thick glass-cloth layers impregnated with a binder for both the primary and backing insulation material. Although it was shown that the lowest heating requirements were obtained with no backing insulation present, some backing insulation probably would be required for strength; hence, such a layer was considered in the case of configuration 8. Results showing the required heating intensity as a function of duration-of-heating period for this arrangement are given in figure 10, which also presents for comparison the data for configuration 1. This comparison shows heater configuration 8 to approach very closely the ultimate in heater design for this particular propeller blade, indicating that the small amount of glass-cloth insulation has very little detrimental effect on the heating efficiency.

It should be pointed out that the magnitude of these gains in heating efficiency resulting from improvements in heater design can be considered applicable only to the particular blade form investigated. If the blade-metal thickness were decreased, the gains would be more pronounced. On the other hand, if the metal thickness were increased, the adverse effects of the heater insulation material would be masked to a greater extent by the increased thermal inertia of the blade, and gains in heating efficiency would be less apparent.

Effect of reduction in heating period on energy requirement.—
The investigations of references 2, 3, and 7 have shown that reductions in the total energy requirement are possible by decreasing the

duration-of-heating period. In order to determine the effect of decreasing the duration-of-heating time on the energy requirement for the configurations of this investigation, curves depicting this relationship were constructed, as shown in figure 11. Also included is a curve for the case of an ideal external heater. These data show the energy requirements to decrease with decreasing heat-on time throughout the entire range of heating period investigated, for all configurations except those with a large amount of backing insulation (configurations 5, 6, and 7). For these arrangements, the energy requirement decreased slightly with decreasing heating time, reaching minimum values at about 10 seconds. Below about 10 seconds, the energy requirements increased for these configurations.

With the exception of the ice formation alone, the greatest decreases in energy requirement were obtained for configurations 1 and 8. For these cases, over 40-percent reduction in energy could be obtained by decreasing the heating period from 20 to 5 seconds. From a comparison of the curves for configuration 1 (blade metal only) and for the case of ice only, it is apparent that an increased reduction in the energy requirement could be achieved through the use of thinner blade metals. The data of figure 11 indicate a relationship between the thermal inertia of a blade and heater combination and the possible reduction in energy requirements resulting from decreasing the heating period - the smaller the thermal inertia, the greater the possible reduction in energy requirement. Thus, the desirability of decreasing the thermal inertia of the system is further emphasized.

Effect of variations in air temperature on heating requirement for configuration 8.- The effect of air-temperature variations on the heating requirement for configuration 8 is illustrated in figure 12, which shows the required heating intensities as a function of heating period for free-air temperatures of 0° , -12° , and -20° F. From these curves, air temperature is shown to have a substantial effect on the heating requirements. As would be expected, the heat requirements are increased with decreasing air temperature. A similar relationship of heat requirement with air temperature was noted in reference 3, in which air temperature was demonstrated to have a dominant influence on the de-icing performance of external blade shoes.

Heater-temperature data for configuration 8.- Values of maximum heater temperature reached during cyclic de-icing of the propeller blade with heater configuration 8 are given in table III for free-air temperatures of 0° , -12° , and -20° F. Also presented in table III are the temperatures the heater would reach with a continuous application of heat of the same intensity as required for the conditions of cyclic de-icing. This provides an indication of the degree of hazard which might result from a cycling-system failure wherein the power to the blade heater would be supplied for an indefinite period.

The data of table III show that safe operating temperatures were not exceeded for configuration 8 under any of the conditions of the tests. Thus, it appears that the maximum heater temperature reached during normal operation, or even upon failure of the power-cycling system, can be maintained within safe limits for most insulation materials through proper heater design.

Remarks Concerning the Feasibility of Utilizing Internal Electric Heaters for Propeller De-Icing

The data presented herein will be examined from the thermal standpoint as to the feasibility of utilizing internal electric heaters for the cyclic de-icing of propellers. Since the tubular-type heater has been demonstrated to be impractical from considerations of efficiency and safety, these remarks will be confined to the internal shoe-type heater.

The practicability of utilizing an internal blade heater depends on several factors. Among these are the heating requirements and the maximum heater temperatures. An indication of the feasibility of employing an internal heater from the heating-requirement standpoint can be obtained from a comparison of the requirements for an efficient design of internal heater with those for an external blade shoe of current design. Such a comparison is made in figure 13, which presents curves of heating requirement as a function of heating period for internal heater configuration 8 and an external blade shoe composed of rubber outer and inner insulation layers, respectively, 0.015 and 0.060 inch thick. The data for the external blade shoe were taken from figure 13 of reference 3. The internal heater is shown to compare favorably with the external blade shoe, particularly during the longer heating periods, when the heating requirements are less for the internal heater. It should be noted that the data for the two heater configurations are not strictly comparable, due to the fact that the blade forms were not identical. In the case of the external-blade-shoe study, the blade metal in the leading-edge region was substantially thicker than that for the internal-heater investigation, which would cause the heating requirements to be somewhat higher for the external shoe than if the thinner blade metal had been considered. Nevertheless, the data presented in figure 13 are sufficiently indicative of the relative heating values to conclude that for an efficient design of internal heater and blade combination the heating requirements are approximately the same as for currently employed external blade shoes.

The values of maximum heater temperature have been shown to be well within safe operating limits for most insulation materials for the case of an efficient internal-heater design. Thus, from the heater-temperature standpoint, internal blade heating is quite feasible.

An advantage of the internal heater over the external shoe is that the insulation materials can be selected primarily from their thermal properties, rather than from their abrasion-resistance characteristics, thus enabling more effective designs. The primary disadvantage of an internal heater is the complication and expense involved in the event that repairs to the heater become necessary.

CONCLUSIONS

Based on an analytical study of two types of internal-heater arrangements for cyclic de-icing of hollow steel propellers, the following conclusions were drawn:

1. The internal tubular heater of the type tested is an inefficient and impractical configuration for cyclic de-icing applications.
2. The internal shoe-type heater appears to be the most efficient arrangement, and for this type heater, considerable saving of energy can be obtained by minimizing the amount of electrical insulation material surrounding the heater element.
3. The most efficient application of heat appears to be one approximating a uniform distribution at the outer surface of the blade.
4. Heating requirements for an efficient design of internal shoe-type heater are approximately the same as those for currently employed external blade shoes.
5. In general, a reduction in the total energy requirements can be effected by applying higher heating intensities for shorter durations of time. For an efficient design of internal shoe-type heater, and for a total-cycle time of 80 seconds, by operating a 5-second duration of heating time the total energy can be decreased to less than 60 percent of that required for operation at a 20-second heating period.
6. The maximum heater temperatures reached under conditions of cyclic de-icing are dependent on the heating intensity, and are excessively high for the tubular-type heater. For an efficient design of internal shoe-type heater, however, the maximum heater temperatures are within safe limits of operation for existing insulation materials.

Ames Aeronautical Laboratory
National Advisory Committee for Aeronautics
Moffett Field, Calif., Aug. 20, 1953

REFERENCES

1. Lewis, James P., and Stevens, Howard C., Jr.: Icing and De-Icing of a Propeller with Internal Electric Blade Heaters. NACA TN 1691, 1948.
2. Weiner, Frederick: Further Remarks on Intermittent Heating for Aircraft Ice Protection. ASME Transactions, vol. 73, no. 8, Nov. 1951, pp. 1131-1137.
3. Neel, Carr B., Jr.: An Investigation Utilizing an Electrical Analogue of Cyclic De-Icing of a Hollow Steel Propeller with an External Blade Shoe. NACA TN 2852, 1952.
4. Bergrun, Norman R.: An Empirical Method Permitting Rapid Determination of the Area, Rate, and Distribution of Water-Drop Impingement on an Airfoil of Arbitrary Section at Subsonic Speeds. NACA TN 2476, 1951.
5. Lewis, William, and Bergrun, Norman R.: A Probability Analysis of the Meteorological Factors Conducive to Aircraft Icing in the United States. NACA TN 2738, 1952.
6. Lewis, James P.: De-Icing Effectiveness of External Electric Heaters for Propeller Blades. NACA TN 1520, 1948.
7. Tribus, Myron: Intermittent Heating for Aircraft Ice Protection with Application to Propellers and Jet Engines. ASME Transactions, vol. 73, no. 8, Nov. 1951, pp. 1117-1130.

TABLE I.— VALUES OF PHYSICAL PROPERTIES SELECTED FOR
BLADE METAL, ICE ACCRETION, AND HEATER MATERIALS

Component		Material	Density, lb/ft ³	Specific heat, Btu/lb, °F	Thermal conductivity, Btu/hr, ft ² , °F/in.
Blade metal		Steel	490	0.107	300
Ice accretion		Ice	50	0.47	14
Tubular heater	Tube	Stainless steel	494	0.117	139
	Insulation	Magnesium oxide	181	0.209	8.75
	Heater wire	Nickel- chromium steel	525	0.104	Not considered
Shoe-type- heater insulation		Rubber	82	0.31	1.42
		Glass cloth with binder	82	0.15	0.86

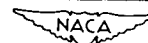


TABLE II.— MAXIMUM HEATER TEMPERATURES REACHED DURING CYCLIC DE-ICING OF BLADE WITH AN INTERNAL SHOE-TYPE HEATER

Configuration	Heating intensity, ¹ watts/in. ²	Duration of heat-on time, sec	Maximum heater temperature, °F
1	7.25	20	36
	10.0	10	36
	16.6	5	37
2	8.45	20	165
	13.2	10	240
	25.9	5	420
3	7.9	20	155
	11.6	10	210
	20.8	5	350
4	7.9	20	110
	11.6	10	140
	21.3	5	230
5	10.4	20	205
	19.1	10	315
	42.7	5	515
6	9.2	20	190
	16.8	10	290
	39.1	5	530
7	10.1	20	205
	17.6	10	295
	38.4	5	490
8	7.35	20	84
	10.1	10	100
	17.0	5	145

¹Heating intensities presented are minimum values required for de-icing at each condition.



NOTE: Liquid-water content, 0.1 gm/m³; free-air temperature, -12° F; total cycle time, 80 seconds; forward true airspeed, 300 mph; propeller speed, 1100 rpm; pressure altitude, 20,000 ft.

TABLE III.- MAXIMUM HEATER TEMPERATURES REACHED DURING CYCLIC DE-ICING AND CONTINUOUS HEATING FOR CONFIGURATION 8 OF INTERNAL SHOE-TYPE HEATER

Free-air temperature, °F	Heating intensity, ¹ watts/in. ²	Duration of heat-on time, sec	Maximum heater temperature, °F	Heater temperature with continuous heating, °F
0	5.0	20	68	72
	6.7	10	80	90
	11.0	5	105	130
-12	7.35	20	84	88
	10.1	10	100	118
	17.0	5	145	190
-20	9.2	20	95	104
	12.7	10	117	140
	21.65	5	170	240

¹Heating intensities presented are minimum values required for de-icing at each condition.



NOTE: Liquid-water content, 0.1 gm/m³; total cycle time, 80 seconds; forward true airspeed, 300 mph; propeller speed, 1100 rpm; pressure altitude, 20,000 ft.

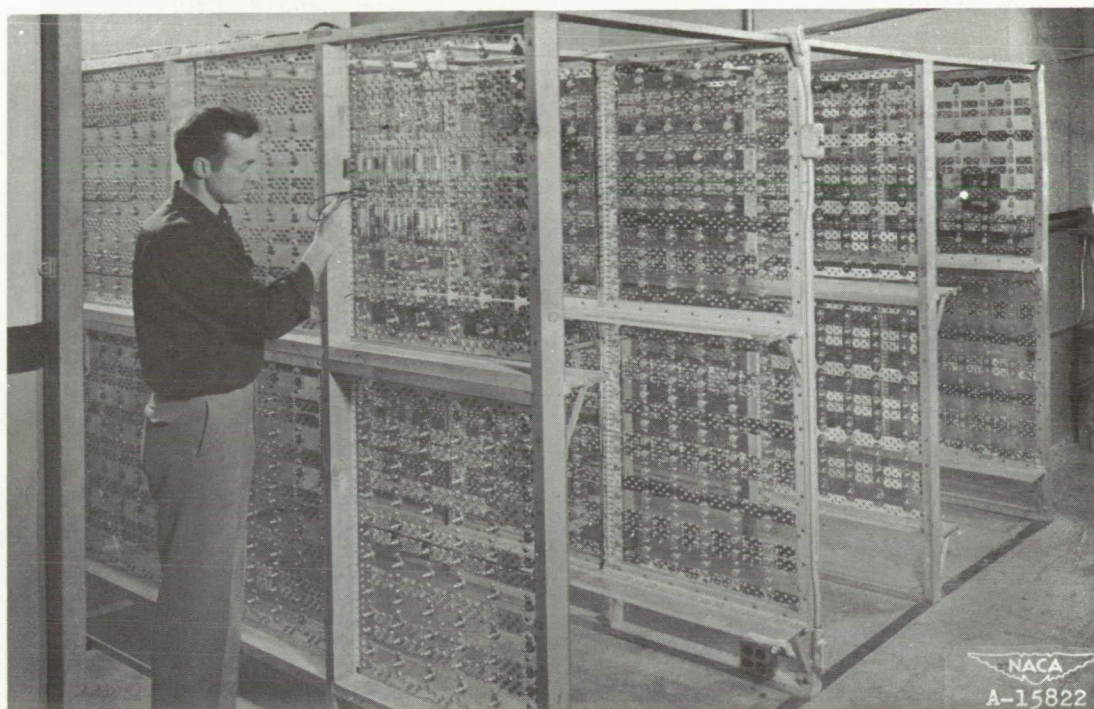


Figure 1.— Electrical analogue used in the investigation of propeller cyclic de-icing.

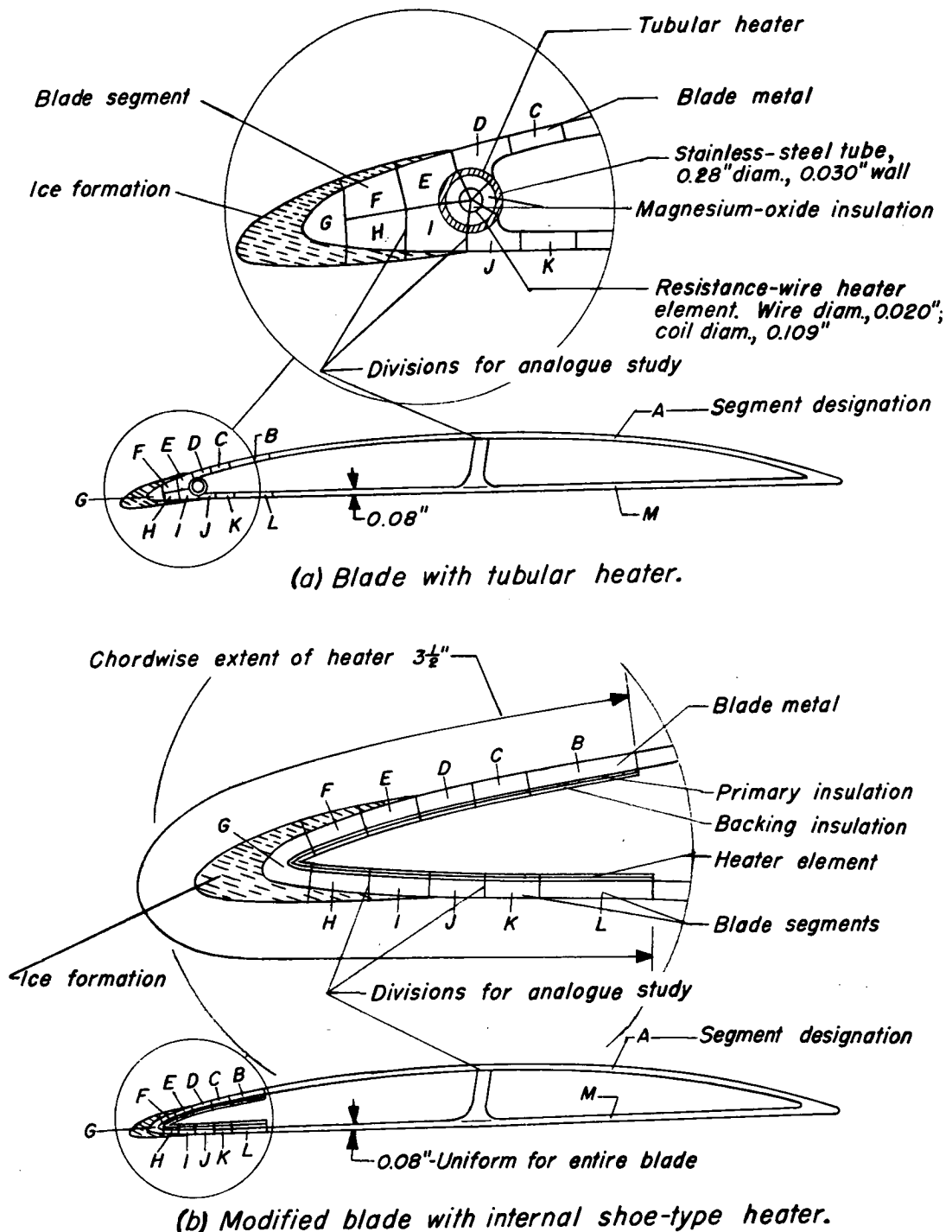


Figure 2.-Cross-section contours of propeller blade at station 48 showing details of ice formation and the two heater configurations investigated.

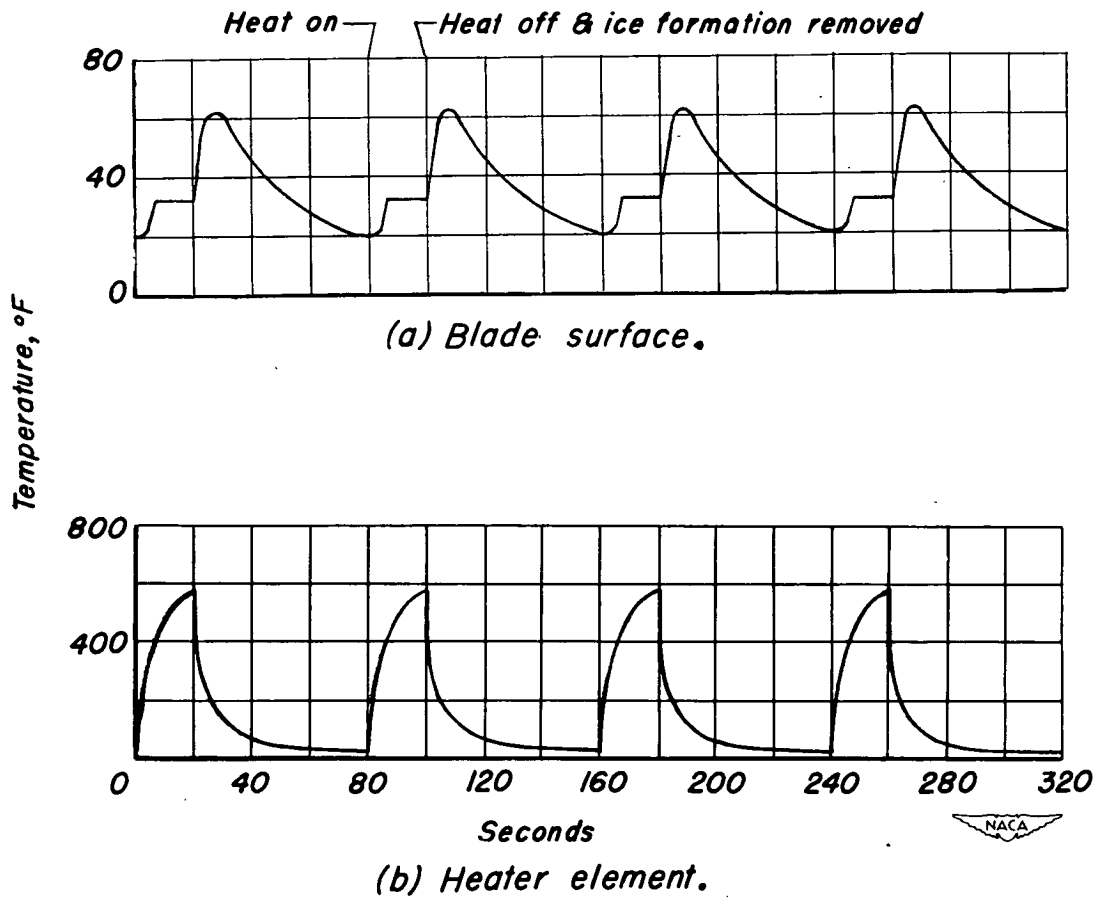


Figure 3.- Typical data obtained with electrical analogue for one segment during simulated cyclic de-icing of a propeller blade with an internal tubular heater.

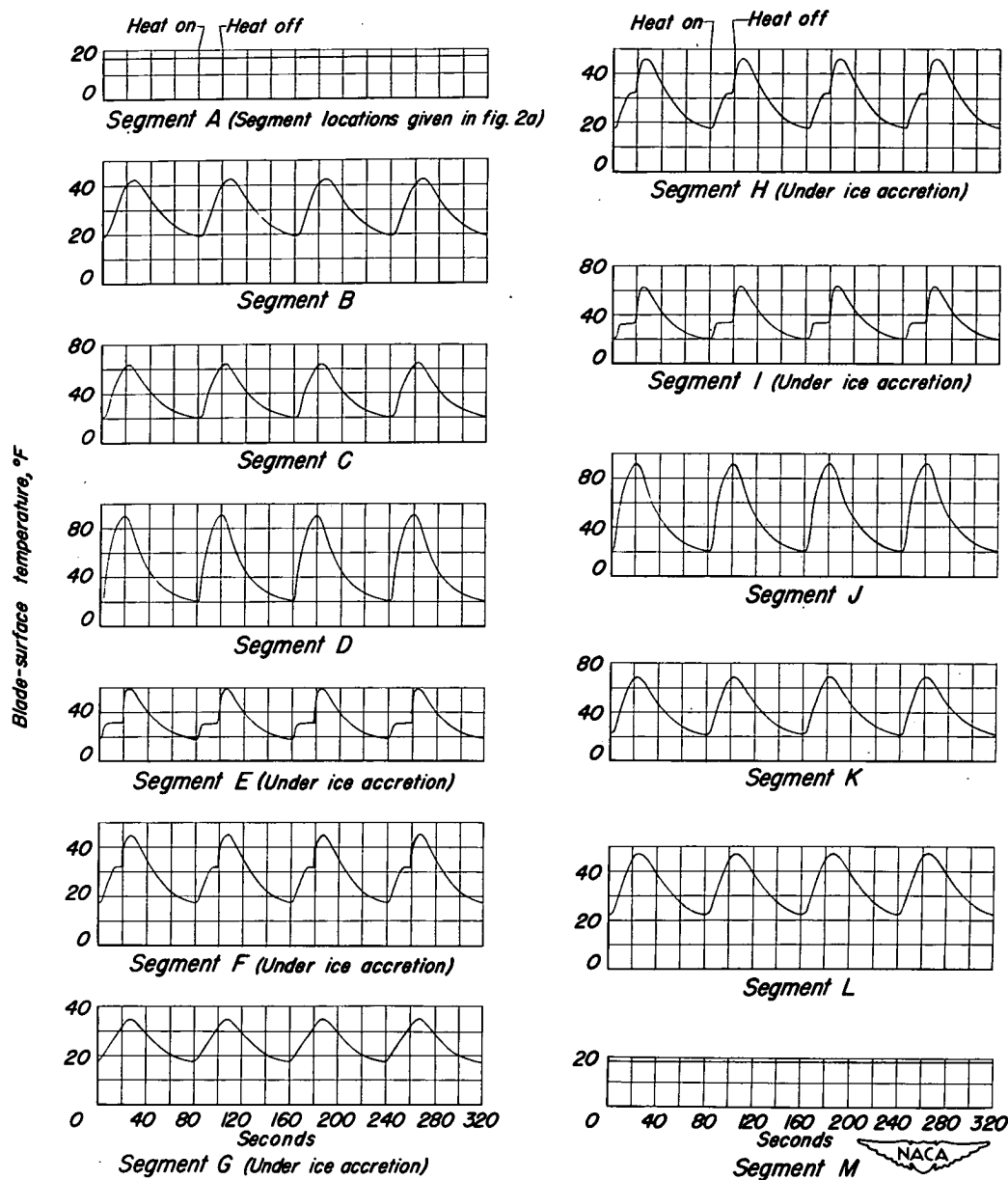


Figure 4.- Typical blade-surface-temperature data obtained with electrical analogue during simulated cyclic de-icing of a propeller blade with an internal tubular heater.

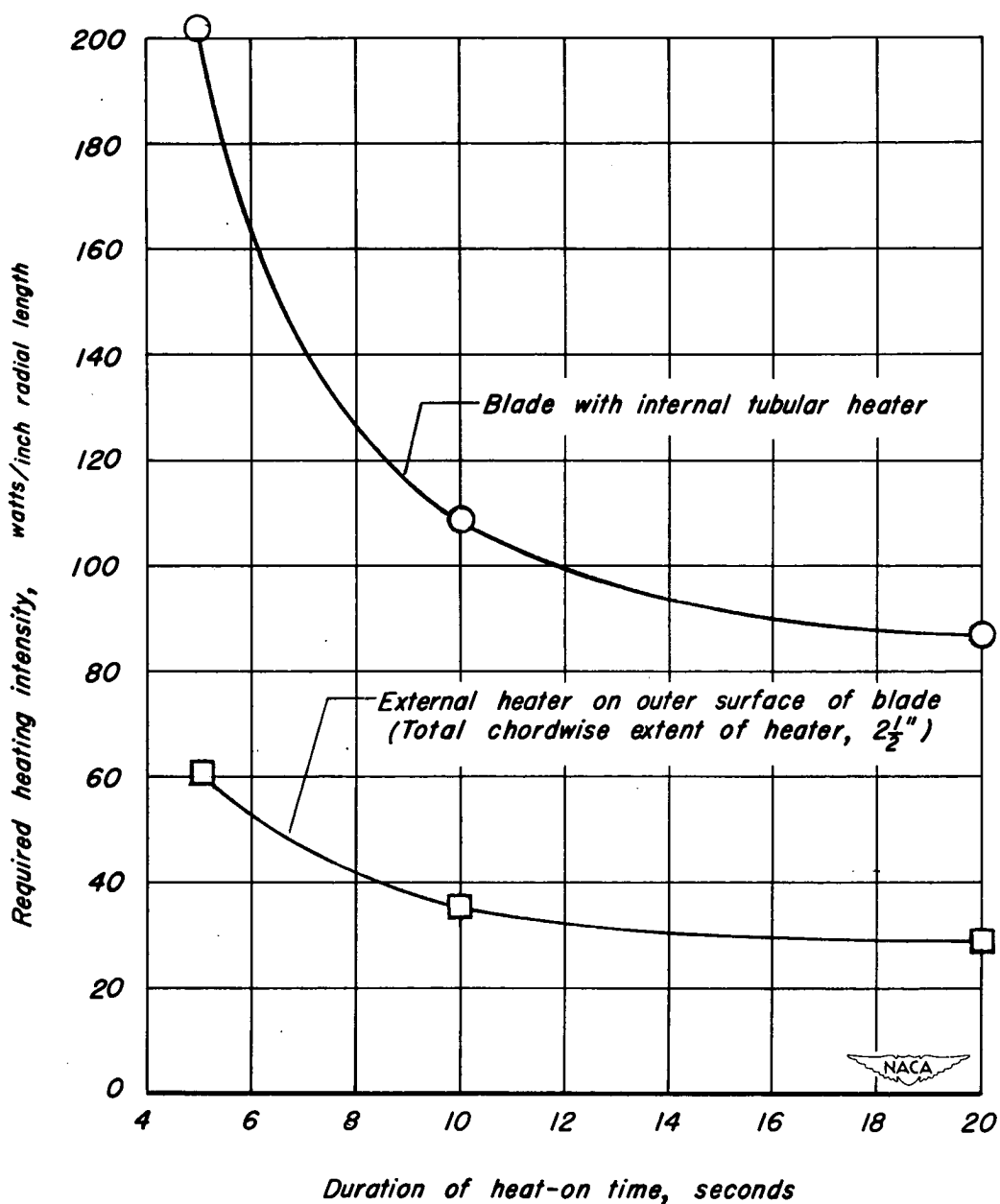


Figure 5.- Heating intensity required for de-icing as a function of cyclic heating time on for internal tubular heater and for case with heat applied uniformly at outer surface of blade.

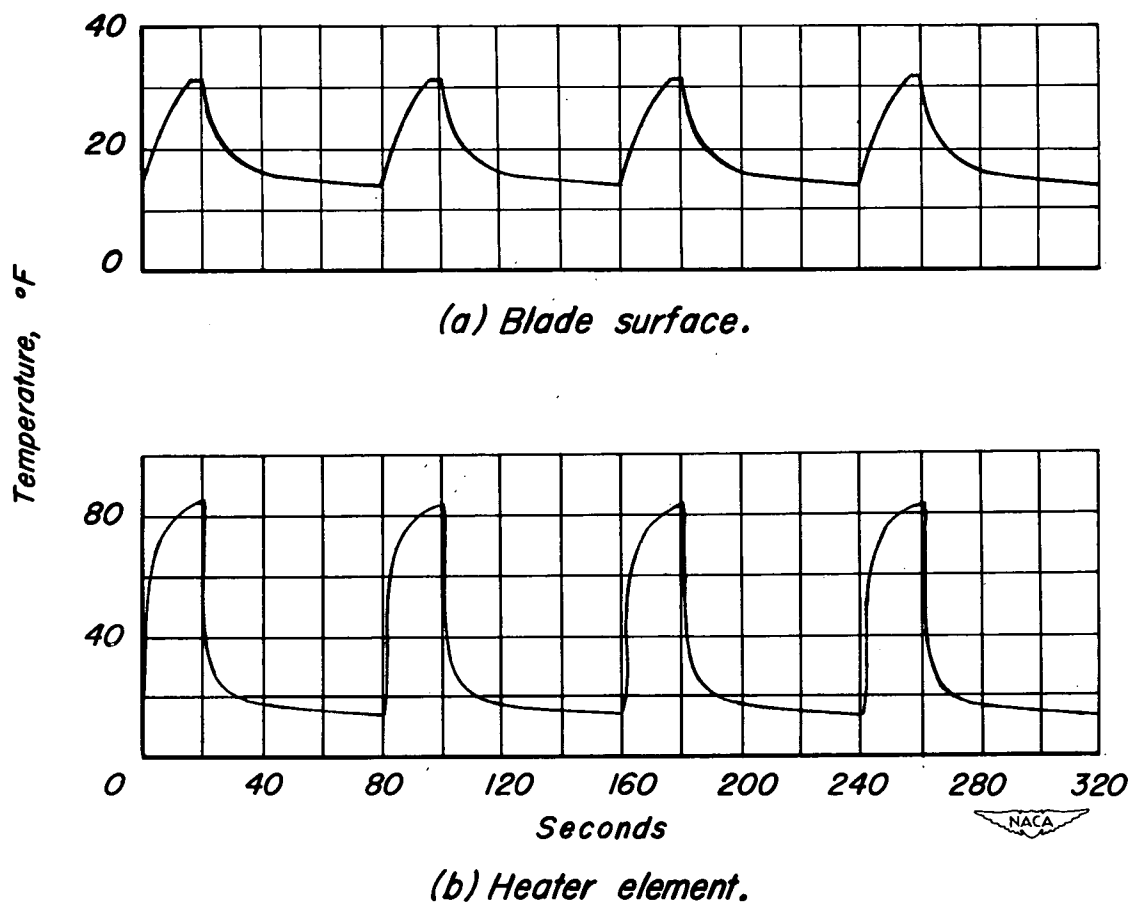


Figure 6.- Typical data obtained with electrical analogue for one blade segment during simulated cyclic de-icing of a propeller blade with an internal shoe-type heater.

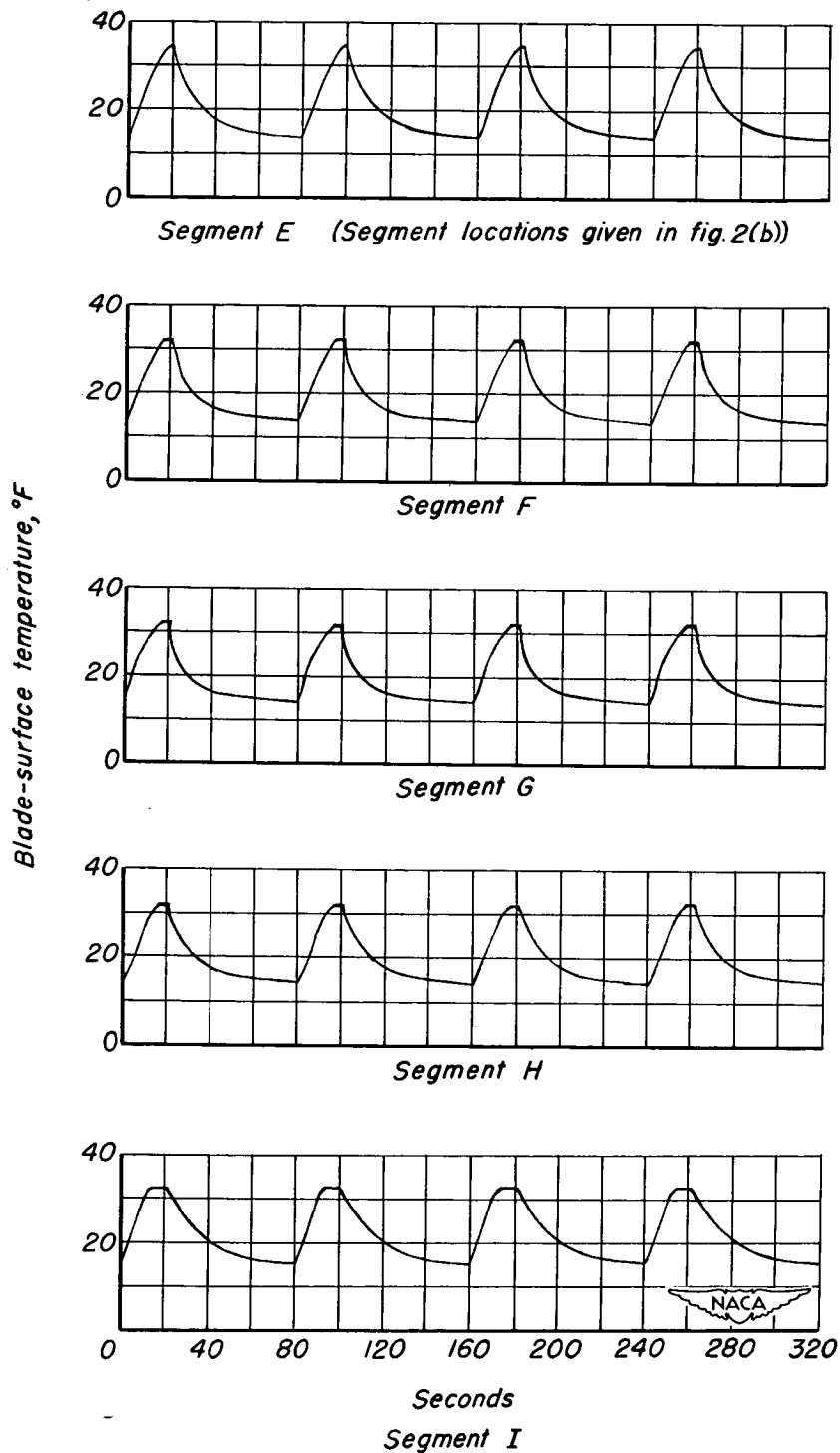


Figure 7.- Typical blade-surface temperatures under ice accretion obtained with electrical analogue during simulated cyclic de-icing of a propeller blade with an internal shoe-type heater.

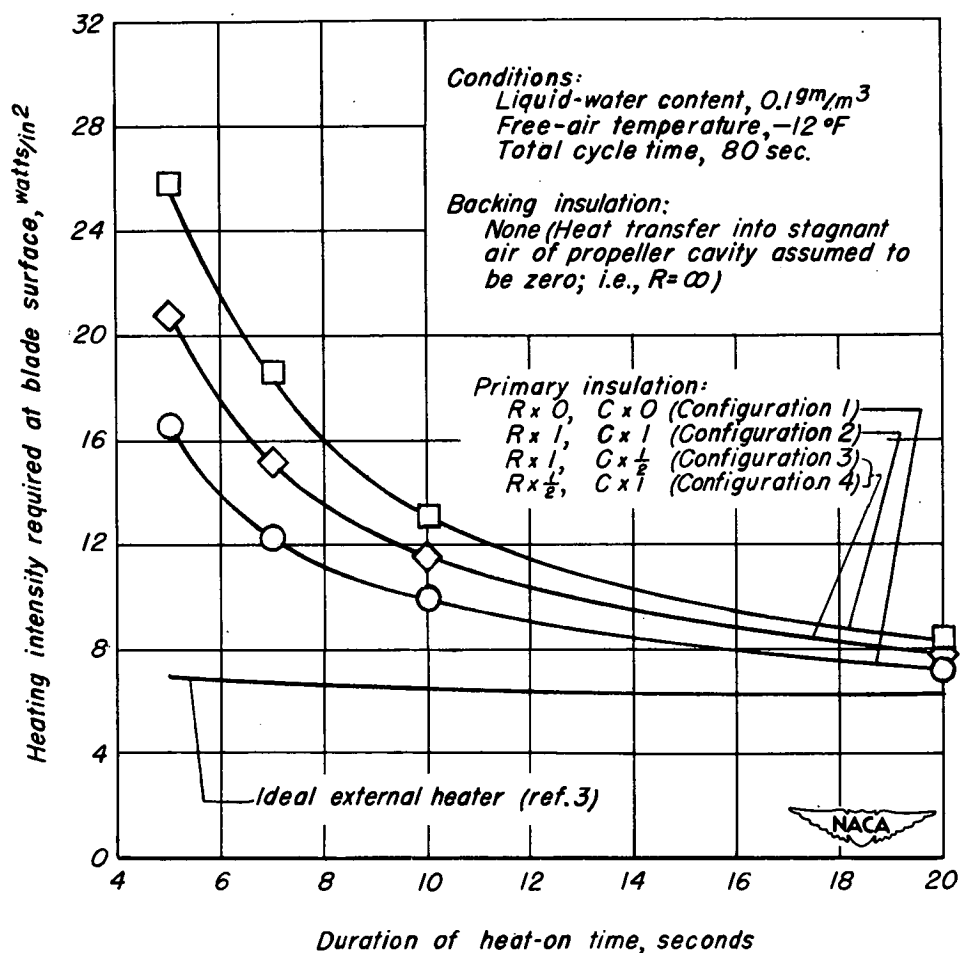


Figure 8.- Effect of variations in properties of primary insulation layer on the heating intensity required for cyclic de-icing. Values of thermal resistance, R , and thermal capacity, C , based on a rubber insulation layer 0.03 inch thick.

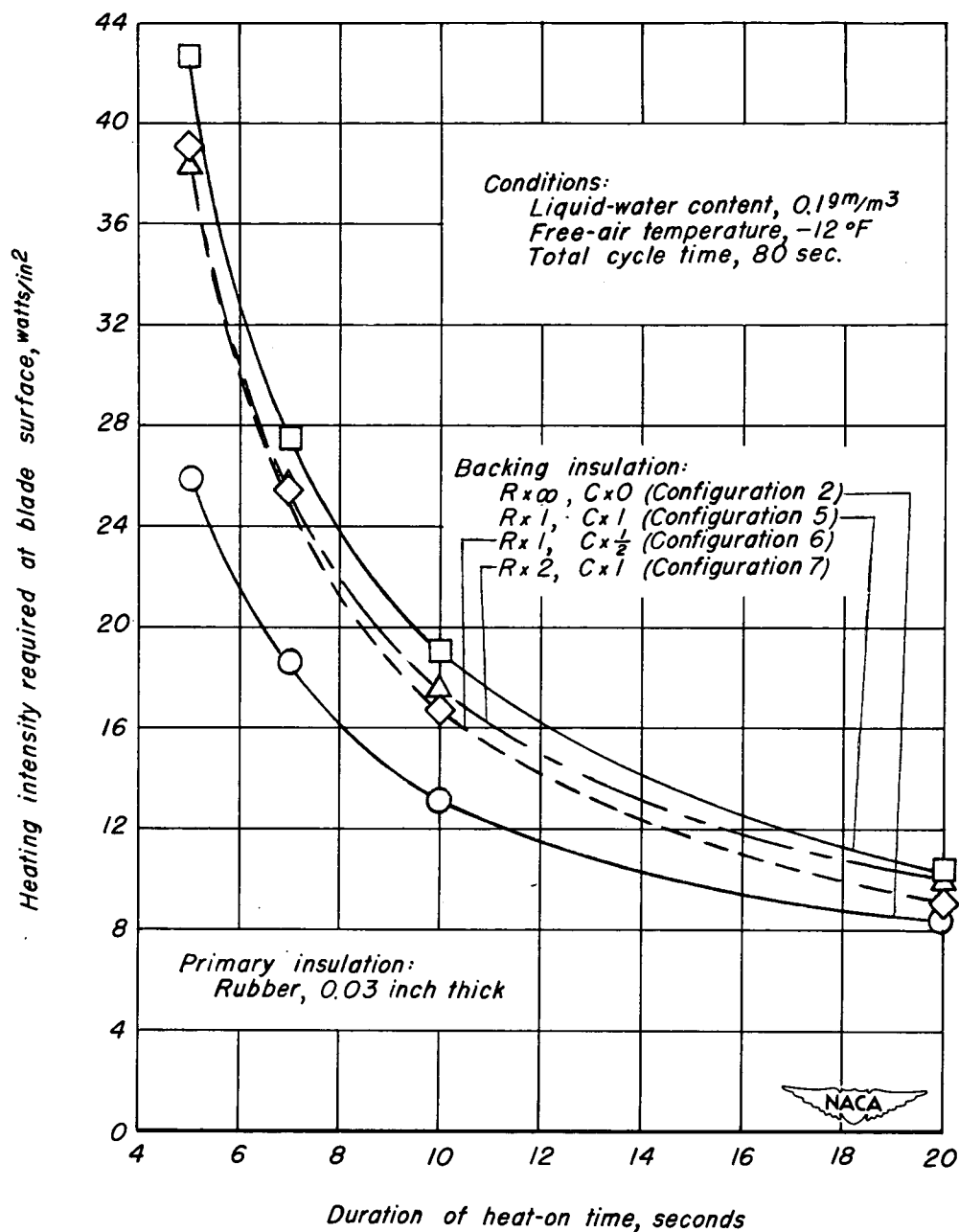


Figure 9.- Effect of variations in properties of backing insulation layer on the heating intensity required for cyclic de-icing. Values of thermal resistance, R , and thermal capacity, C , based on a rubber insulation layer 0.03 inch thick.

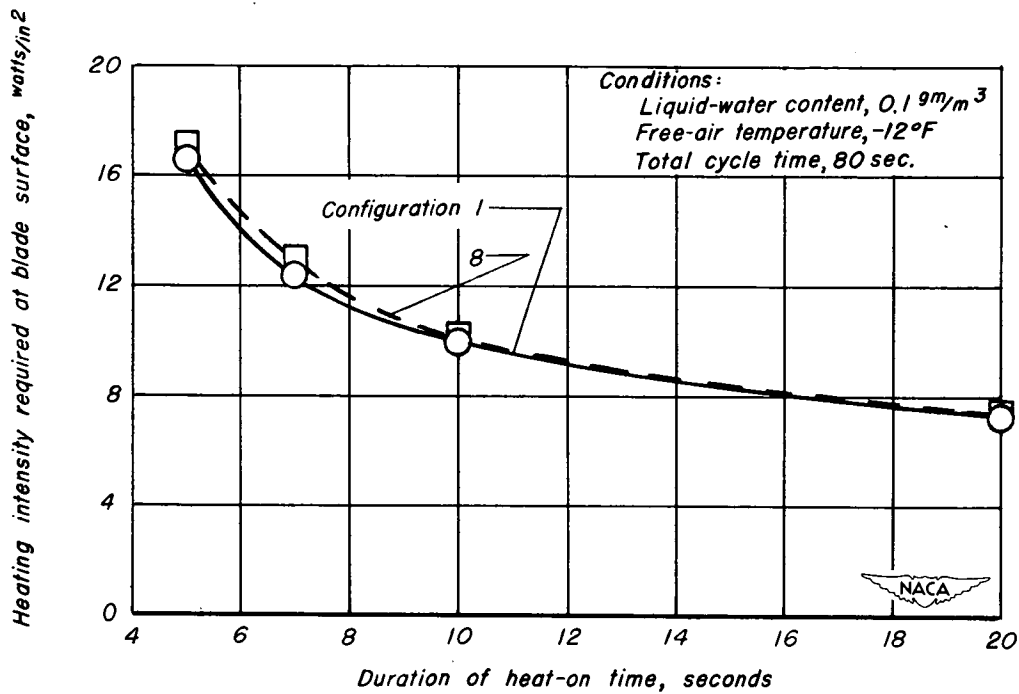


Figure 10.- Heating intensity required for de-icing as a function of cyclic heating time on for an internal shoe-type heater having desirable thermal characteristics (configuration 8), as compared with the minimum required heating intensity (configuration 1).

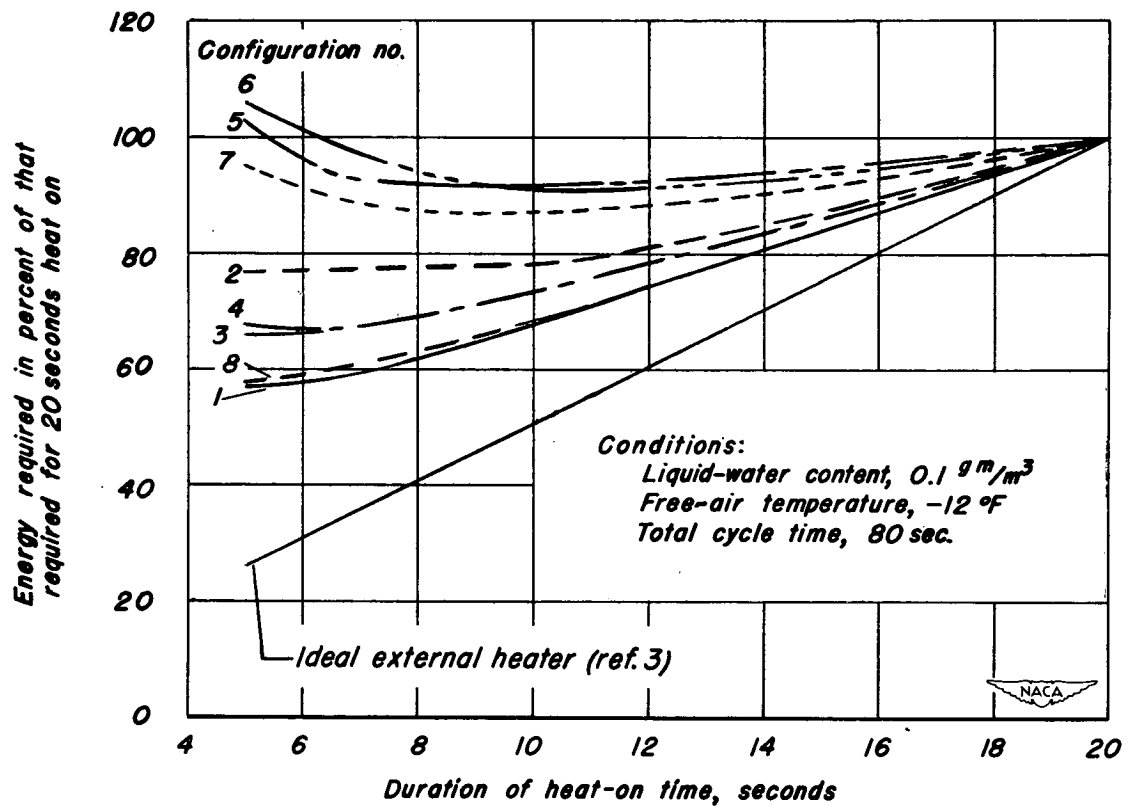


Figure 11.— Effect of varying the heat-on time on the energy required to cyclically de-ice the propeller blade using an 80-second cycle. internal shoe-type heater.

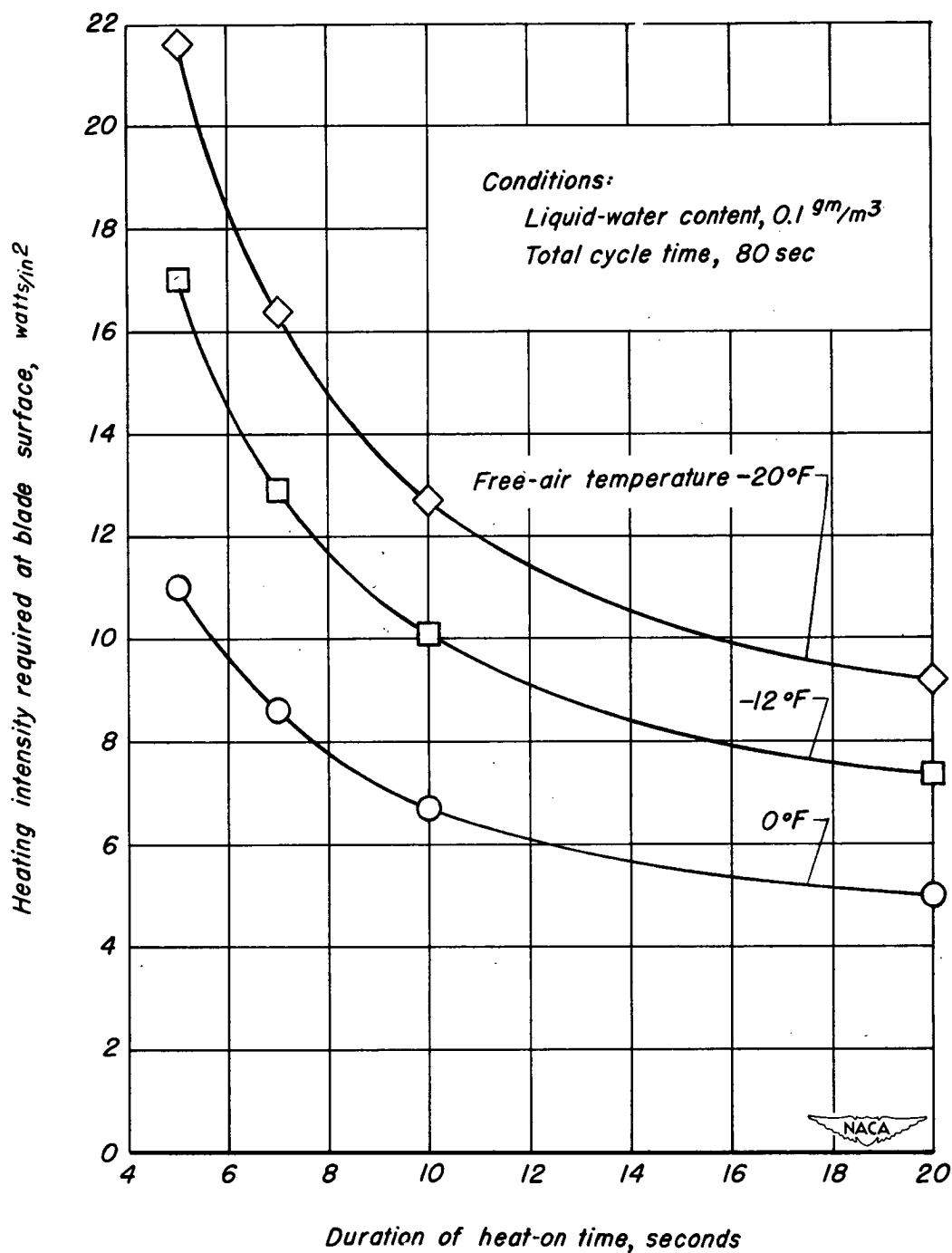


Figure 12.- Heating intensity required for de-icing as a function of cyclic heating time on for various free-air temperatures. Configuration 8 of internal shoe-type heater.

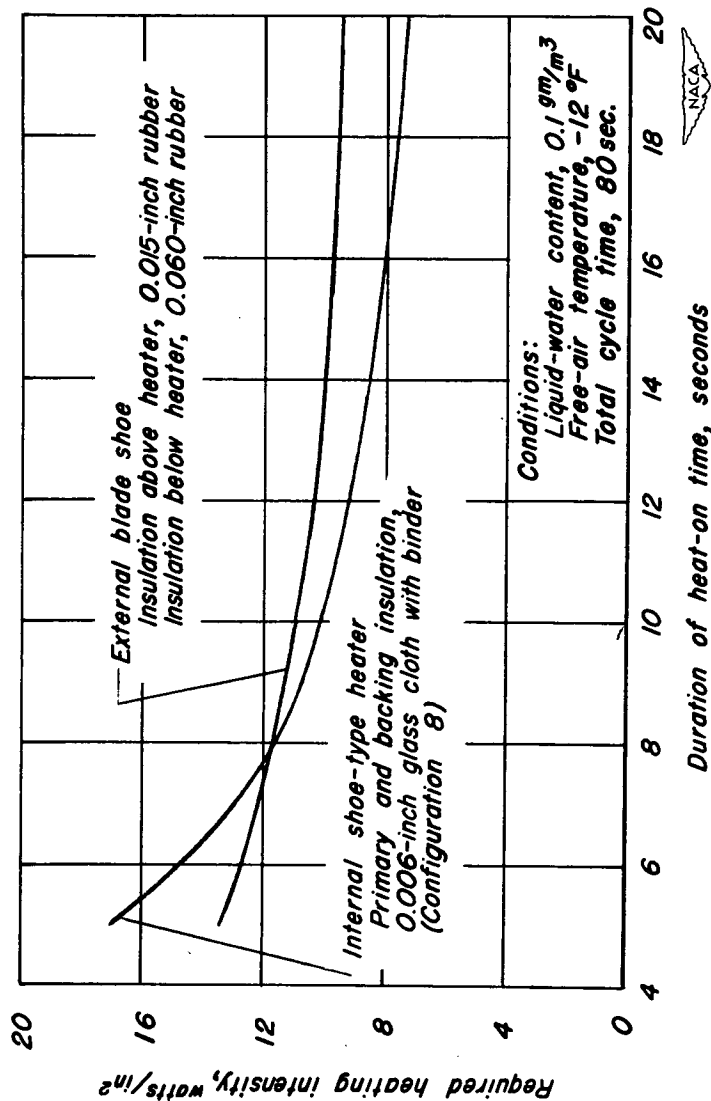


Figure 13.— Comparison of heating requirements for an efficient design of internal heater with those for an external blade shoe of current design. (External blade—shoe data taken from fig.13, ref.3.)